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FLYGTEKNISKA FÖRSÖKSANSTALTEN

THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN

MEDDELANDE 129

REPORT 129

A COMBINED PROBE FOR MEASUREMENT OF MASS FLOW, STAGNATION TEMPERATURE, AND STAGNATION PRESSURE IN SUPERSONIC BOUNDARY LAYERS

BY

Gunnar Hovstadius

STOCKHOLM 1977

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(6) # A COMBINED PROBE FOR MEASUREMENT OF MASS FLOW, STAGNATION TEMPERATURE, AND STAGNATION PRESSURE IN SUPERSONIC BOUNDARY LAYERS,

by

(10) *Gunnar Hovstadius*

(11) Mar 77

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SUMMARY

A combined probe for measurement of mass flow, stagnation temperature, and stagnation pressure in supersonic boundary layers has been built and tested. The mass flow is evaluated from the rate of change of pressure in a volume connected to the probe. The probe incorporates a thermocouple and provision is made for the establishment of a controlled mass flow past the thermocouple during the temperature measurements.

The probe has been tested at different pressures and temperatures in the boundary layer on the nozzle wall of the FFA Hyp 500 facilities. The results were compared with the results from simultaneous measurements with the AVA combined pressure-temperature probe. The results agreed within the expected limits of accuracy.

Stockholm, March 1977

EINE SONDE FÜR MESSUNG VON MASSENSTROM, RUHETEMPERATUR UND RUHEDRUCK IN ÜBERSCHALL-GRENZSCHICHTEN

von

Gunnar Hovstadius

ZUSAMMENFASSUNG

Eine kombinierte Sonde zur Messung des Massenstromes, der Ruhetemperatur und des Ruhedruckes ist konstruiert und getestet worden. Der Massenstrom wird ermittelt aus den Druckänderungen in einem Volumen, das mit der Sonde verbunden ist. Innerhalb der Sonde sitzt ein Thermoelement und es ist dafür gesorgt worden, dass sich ein kontrollierter Massenstrom um das Thermoelement während der Temperaturmessungen einstellt.

Die Sonde ist bei verschiedenen Drücken und Temperaturen in der Grenzschicht der Düsenwand des FFA HYP 500 Kanals getestet worden. Die Ergebnisse sind mit den simultanen Messungen der kombinierten Druck- und Temperatur-AVA-Sonde verglichen worden. Die Ergebnisse stimmen in der erwarteten Genauigkeit überein.

UNE SONDE COMBINÉE POUR DES MÉSURES DE L'ÉCOULEMENT DE MASSE, DE TEMPÉRATURE TOTALE, ET DE PRESSION TOTALE DANS DES COUCHES LIMITES SUPERSONIQUES

par

Gunnar Hovstadius

RÉSUMÉ

Une sonde combinée pour mesurer l'écoulement de masse, de pression totale et de température totale dans des couches limites supersoniques est construite et examinée. L'écoulement de masse est évalué à partir des variations de pression dans un volume attaché à la sonde. Une thermocouple est située dans la sonde et pendant les mesures de température un écoulement de masse contrôlé est établi autour de la thermocouple.

La sonde est examinée dans des conditions différentes de pression et de température dans la couche limite, qui se développe sur la paroi de la tuyère de la soufflerie FFA HYP 500. Les résultats sont comparés avec les mesures effectuées simultanément avec la sonde combinée (pression et température) d'AVA. Les résultats sont en accord dans les limites de précision expectées.

CONTENTS

A COMBINED PROBE FOR MEASUREMENT OF MASS FLOW, STAGNATION TEMPERATURE, AND STAGNATION PRESSURE IN SUPERSONIC BOUNDARY LAYERS

by

Gunnar Hovstadius

1. INTRODUCTION

In order to define fully a steady flow, it is necessary to know three flow properties. Usually, these are obtained by measuring some of the following quantities: pitot pressure, static pressure, stagnation temperature, mass flow, and, when applicable, the stagnation pressure of the tunnel. Any three of these quantities can be used to derive the others. The equations to derive these quantities are conveniently gathered in Ref. [1], where it is also pointed out that the most favourable quantities to measure would be: stagnation temperature, mass flow, and pitot pressure. No effort has previously been made to build a probe for measuring these three variables.

During the last few years, different probes for the measurement of flow properties in supersonic boundary layers have been tested at FFA, Refs. [2]-[5]. The work has mainly been concerned with the development of mass-flow probes. The first mass-flow measuring system at FFA, developed by Stalker, Ref. [2], used a sonic orifice for the determination of the mass flow. This system had the drawback of requiring a rather high pressure in order to avoid drastic changes in the effective area of the sonic orifice, which in turn led to detachment of the shock at the probe inlet. Side-by-side measurements of the flow properties in the boundary layer on the nozzle wall of the Hyp 500 wind tunnel were later made with a combined pressure-temperature probe from AVA and a mass flow probe, Ref. [4].

An alternative method of mass-flow measurement, which instead used the pressure derivative in a closed system to derive the mass flow, was thereafter developed, Ref. [5]. This technique

had certain advantages over the earlier technique. The pressure level in the measuring system could be considerably reduced, thereby reducing the risk of shock detachment at the probe inlet. Also, the number of parameters in the determination of the mass flow decreased. The new technique for mass-flow measurement allowed the installation of a thermocouple behind the entrance of a mass-flow probe, without causing detachment of the shock. This report describes such a combined mass-flow-stagnation-temperature probe. It has been tested at different Reynolds numbers in the M4 nozzle of the FFA Hyp 500 facilities. The results are compared with the results obtained from measurements with a combined pressure-temperature probe. This probe has earlier been tested simultaneously with a conical equilibrium probe in a turbulent boundary layer at $M_\infty = 5$, Ref. [6]. The measured stagnation temperatures in those tests were in very good agreement.

2. TEST CONDITIONS

The experiments were carried out in the Hyp 500 wind tunnel at FFA. The tunnel is a blow-down-to-atmosphere wind tunnel with contoured axisymmetric nozzles and an open jet test section, 50 cm in diameter, Ref. [7].

In the present tests the tunnel conditions were:

Mach number	4	4	4
Stagnation pressures	1.5	1.1	1.1 MPa
Stagnation temperatures	320	470	590 K

The measuring position was located 1 cm downstream from the end of the nozzle so that the probes could be kept outside the nozzle. The probes could thus be protected from the high loads during the starting up of the tunnel.

The Mach number distribution in the M4 nozzle is shown in Fig.1.

3. TEST EQUIPMENT

3.1 The probes used

The combined mass-flow-stagnation-temperature probe was tested side by side with the AVA combined pressure-temperature probe in the boundary layer on the nozzle wall of the Hyp 500 wind tunnel.

The probes were mounted on a traversing system that made it possible to traverse the entire boundary layer during a run. They could be stopped for measurement at an arbitrary position in the boundary layer.

3.2 The AVA combined pressure-temperature probe

The AVA-probe is shown in Fig. 3. A thermocouple is placed immediately behind the opening of a pitot tube. The thermocouple is built from sheathed thermocouple wire (Thermocoax), 0.1 mm in diameter. The ratio between the diameter and the length of the wires is small in order to minimize heat losses by conduction. The conductors and the sheath are isolated from each other by Magnesia powder. A system of valves and sonic orifices allows the mass flow through the system to be varied. By closing the valves it is also possible to measure the pitot pressure.

Meier has shown that the recovery factor r_p , where

$$r_p = \frac{T_{om} - T_\infty}{T_o - T_\infty} \qquad (1)$$

of the thermocouple in a probe with suction is strongly dependent on the mass flow past the thermocouple, Ref. [8]. The dependence is shown in Fig. 4. It is seen that there exists a

critical value of the mass flow below which the recovery factor starts to fall. Above this value, r_p is approximately constant.

The probe has to be calibrated. This is made by changing the mass flow through the probe while it is kept in the free stream of the wind tunnel where the temperature is known.

With

$$\frac{T_o}{T_\infty} = 1 + \frac{\gamma - 1}{2} M^2 \tag{2}$$

and Eq. (1), the following expression for T_o is obtained

$$T_o = \frac{T_{om}}{r_p + \dfrac{1 - r_p}{\left(1 + \dfrac{\gamma - 1}{2} M^2\right)}} \tag{3}$$

The normalized mass flow in the boundary layer is obtained from the following expression, Ref. [5]

$$\frac{\rho u}{(\rho u)_\infty} = \left[\frac{T_{s_\infty}}{T_s} \frac{p_s}{p_{s_\infty}} \frac{f(M)}{f(M)_\infty} \frac{(1 + 0.2\ M^2)}{(1 + 0.2\ M^2)_\infty}\right]^{\frac{1}{2}} \tag{4}$$

where

$$f(M) = \frac{1}{2.1328} \left(1.4 - \frac{0.2}{M^2}\right)^{2.5} \tag{5}$$

In the present tests, the area of the suction-controlling sonic orifice was made large enough to keep the mass flow above the critical value in the entire portion of the boundary layer where measurements were made. A more detailed description of the system is given in Ref. [8].

3.3 *The combined mass-flow — stagnation-temperature probe*

The combined mass-flow-stagnation-temperature probe is essentially a combination of the FFA mass-flow probe and the AVA combined pressure-temperature probe. These probes, which are shown in Figs. 2 and 3, are described in detail in Refs. [5] and [8]. A short description will, however, be given below for convenience.

A thermocouple has been installed inside the mass-flow probe, just behind the intake. The system has also been equipped with a valve leading to a small orifice for control of the mass flow during temperature measurements, as suggested by Meier. The combined probe is shown in Fig. 5. For mass-flow measurements the valve to the vacuum system is first opened in order to lower the pressure in the system as much as possible. The mass flow into the probe is calculated from the rate of change of the pressure in the system, after the valve to the vacuum system has been closed. When the pressure in the system is high enough, the shock becomes detached at the probe entrance, and finally the stagnation pressure is reached. Fig. 6 shows two typical pressure recordings. The temperature in the system is controlled by heat exchangers.

In order to obtain the normalized mass flow $\rho u/(\rho u)_\infty$, measurements were made in the free stream and in the boundary layer. If the entrance area A is assumed to be constant throughout the boundary layer, the following expression is obtained, Ref. [5].

$$\frac{\rho u}{(\rho u)_\infty} = \frac{\dot{p}_v \; \sum_n V_n/T_{vn}}{\dot{p}_{v_\infty} \; \sum_n V_n/T_{vn_\infty}} \tag{6}$$

The normalized mass flow is thus given by the ratio of the pressure derivatives times a function of temperature, correcting for different temperature distributions in the system. The correction arises from the fact that the inlet of the system is heated to a temperature close to the stagnation temperature, which, in turn, varies through the boundary layer.

The stagnation-temperature measurements are made according to Meier's technique, described above. A small mass flow past the thermocouple thus has to be established. This is done by opening a valve to a sonic orifice, see Fig. 5. The probe was calibrated in the free stream of the tunnel, and Eq. (3) was used in the data reduction.

4. RECORDING OF DATA

The data were recorded on the Beckman 210 data acquisition system of the Hyp 500 facilities. The system accepts up to 50 low-level analog input signals and records the input signals on magnetic tape in a digital format, compatible with an ICL 1901-AS or IBM 360 computer. Thirty of the fifty low-level analog input channels are wired to signal conditioning units of the constant-current type.

The low-level input cables between the wind tunnel and the system are carefully screened and enclosed in iron tubes to eliminate disturbances from electromagnetic noise fields. The system has eight sampling rates, ranging from 1 Hz to 10 kHz. In the present tests the following variables were recorded:

$$p_o, T_o, p_v, T_1, T_2, T_3, T_4, T_s, \text{ and } y$$

The sampling rate used in the tests was 10 Hz.

5. DATA REDUCTION

The normalized mass flow is obtained from Eq. (6). With the present values of the subvolumes (see Fig. 7) and the corresponding temperatures, one obtains

$$\frac{\rho u}{(\rho u)_\infty} = \frac{\dot{p}_v \left[\frac{18}{T_s} + \frac{25}{T_w + [\theta]_{1n}} + \frac{30}{T_3} + \frac{500}{T_4}\right]}{\dot{p}_{v\infty}\left[\frac{18}{T_s} + \frac{25}{T_w + [\theta]_{1n}} + \frac{30}{T_3} + \frac{500}{T_4}\right]_\infty} \tag{7}$$

The pressure derivatives were obtained from the pressure recordings.

$$[\theta]_{ln} = \frac{\theta_1 - \theta_2}{\ln \frac{\theta_1}{\theta_2}} \tag{8}$$

is the logarithmic mean-temperature difference of the heat exchanger. θ_1 equals the temperature difference between the flow and the wall at the entrance, and θ_2 the difference between the flow and the wall at the exit of the heat exchanger.

The total temperature was calculated by using Eq. (3). The calibration of the recovery factor was made in the free stream of the wind tunnel by varying the sucked mass flow.

6. ACCURACY OF MEASUREMENT

6.1 The mass-flow measurements

The accuracy of the mass-flow measurements depends mainly on the following factors:

a) the accuracy of the pressure recording
b) the temperature distribution in the measuring system
c) the effective area of the supersonic intake of the probe

The different transducers are calibrated to give an error of less than 0.5 % in the region of interest. The temperature distribution is, in principle, accurately measurable, but the approximations used will give rise to an error. The correction for different temperature distributions in the system was, however, smaller than 0.3 %.

The intake area of the probe is assumed to be constant throughout the boundary layer. This assumption may be violated by detachment of the shock and by Reynolds - number effects in the boundary layer.

These effects are discussed in detail in Ref. [5], where it is shown that mass-flow measurements can be made with an accuracy within ± 2 % using a probe without a thermocouple.

The insertion of a thermocouple in the mass-flow probe could, of course, introduce an error in the measurements. The tests show, however, no influence of the thermocouple.

6.2 The temperature measurements

The accuracy of the temperature measurements depends mainly on the conversion and recovery factors of the thermocouple. The main difficulty is to determine the recovery factor. At low stagnation temperatures, the recovery factor mainly depends on the mass flow through the probe, and it can be calibrated as described above. At higher temperatures, it was found that the temperature measured by the thermocouple in the mass-flow probe was also influenced by conduction.

According to the manufacturer, the error in the thermovoltage and the conversion factor gives an error in temperature of 2.2 % when measured in degrees centigrade. This gives an error of less than 1 % in the absolute temperature. For the AVA probe, the error in the recovery factor is assumed to be smaller than 1 %, giving a maximum total error of less than 2 %.

The accuracy in determination of the recovery factor of the thermocouple in the mass-flow probe is dependent on the temperature level. Below a stagnation temperature of 500 K the error is 1.5 %. Between 500 and 600 K the influence of conduction becomes more pronounced, and the error increases to 2.5 %, giving total errors of 2.5 and 3.5 %, respectively.

6.3 *Probe positions in the boundary layer*

The probe positions, relative to the wall, differed by about 1 mm between the probes, the FFA probe being closest to the wall. Each measurement position in the boundary layer, therefore, gave two points with a difference of 1 mm in wall distance in the figures. The difference in probe positions was also measured by comparing the stagnation pressures measured by the two probes.

The position in the boundary layer was measured relative to the probe support, which was not rigidly attached to the nozzle. The nozzle moves up to 0.4 mm during a run. Therefore, there may be an error of 0.4 mm in wall distance.

7. RESULTS AND DISCUSSION

7.1 *The mass-flow measurements*

The mass flow in the boundary layer on the M4 nozzle wall of the FFA Hyp 500 wind tunnel has been measured with the new combined mass-flow-stagnation-temperature probe. The results of the measurements have been compared with earlier measurements made with a pure mass-flow probe, and calculated mass flows, obtained from measurements of total temperature and stagnation pressure. The results are shown in Figs. 9-12.

Fig. 9 shows the mass flow measured with and without a thermocouple in the mass-flow probe. As seen, the results are practically identical. The tests were carried out under the same stagnation conditions as those reported in Ref. [5], i.e.: p_o = 11 bar, T_o = 475 K. Fig. 10, taken from the same report, shows good agreement between the measured mass flow and that calculated from pressure and temperature measurements with the AVA probe.

Figs. 11 and 12 show the results of the comparative measurements with the mass-flow probe having a thermocouple behind the inlet and the AVA probe. The stagnation conditions were p_o = 15.3, T_o = 315 and p_o = 10, T_o = 570 K, respectively, giving free-stream Reynolds numbers of $6.5 \cdot 10^7$/m and $1.5 \cdot 10^7$/m. As seen, the boundary-layer thickness grows with decreasing Reynolds numbers.

The agreement between the measurements was satisfactory throughout the entire boundary layer, in all tested conditions. A minor scatter was caused by the fact that the boundary layer changed somewhat in form during the run due to the heating of the nozzle wall. Consequently, the mass flow at a given position varied somewhat with time. A second factor that gave rise to scatter in the data was the movement of the nozzle relative to the probe support. This movement was of the order 0.4 mm during a run.

From the pressure recordings it was seen that the shock at the probe entrance detached somewhat earlier for a probe with thermocouple than for a probe without. This was expected and caused by the pressure rise behind the probe entrance due to the area blockage with the thermocouple present.

7.2 *The temperature measurements*

The temperature measurements were made according to Meier's technique. No problems were encountered with the AVA probe. A very high recovery factor was attained (r_p = 0.992).

The temperature measurements with the thermocouple in the mass-flow probe turned out to be more difficult. Since the probe was originally designed for pure mass-flow measurements, where constant temperature throughout the system is required, it was furnished with thick walls and a cooler. One should, therefore, expect larger heat losses in this probe than in the AVA

probe. The temperatures measured by the thermocouple in the mass-flow probe were also lower than those measured by the AVA probe. Three different thermocouples were tried, all with the same results.

Due to heat losses, the recovery factor of the thermocouple in the mass-flow probe was lower than that of the AVA probe. The losses increased with increasing temperature difference between the probe and the stagnation temperature; therefore, different calibration curves had to be used at different stagnation temperatures in the tunnel. At the highest temperatures, i.e. 590K, the recovery factor also changed with the time. Fig. 8 shows different calibrations of the probes.

During the low-temperature runs, the stagnation temperature was close to room temperature ($T_o \sim 315$ K), and there were no problems with heat conduction. The recovery factor was taken as constant and equal to the free stream value. The resulting temperature profiles are shown in Fig. 13. As seen, there is rather good agreement.

The temperature profiles at $T_o \simeq 475$ K are also in reasonable agreement (see Fig. 14). The deviation between the results is within the expected accuracy.

At $T_o \sim 590$ K, measurement of the stagnation temperature was more difficult. Because of the short running time of the tunnel, it was not possible to wait for the probe to reach temperature equilibrium with the flow. The probe was therefore heated during a large part of each run. This results in a recovery factor, varying, not only with the mass flow through the probe, but also with the time, as seen in Fig. 8. The recovery factor just after starting up of the tunnel, while the probe temperature is still low, is rather low. As the probe moves toward the wall, the stagnation temperature in the boundary layer decreases and thus also the heat conduction. This probably causes the recovery factor to increase, relative to the value obtained in the free

stream. In the data reduction it was impossible to correct for the true recovery factor. A constant value of 0.95 was therefore used. This, of course, causes a larger error at the high-stagnation-temperature tests, compared with the tests with lower stagnation temperatures in the tunnel. The increased temperature in the boundary layer, relative to that measured by the AVA probe, is therefore due to the use of too low a recovery factor, as explained above.

8. CONCLUSIONS

The mass flow and temperature distribution in the boundary layer on the M4 nozzle wall have been measured with a combined mass-flow-stagnation-temperature probe. The measurements were compared with data obtained from the same system without a thermocouple and from measurements with the AVA combined pressure-temperature probe. The agreement between the results of the measurements was within the limits of expected accuracy for all tested conditions.

It is shown that it was possible to incorporate a thermocouple into a mass-flow probe without affecting the mass-flow measurements, provided that the pressure level behind the probe entrance can be kept low enough. The measuring method used made it possible to perform the mass-flow measurements at a sufficiently low pressure.

Due to the different designs of the probes, the thermocouple in the mass-flow probe was more sensitive to heat conduction than was the thermocouple in the AVA probe. At stagnation temperatures below 500 K, it was possible to calibrate the temperature measurements of the mass-flow probe to within about 2.5 %; at higher temperatures the error increased to about 3.5 %.

The main advantage of a combined mass-flow-stagnation-temperature probe is that it enables measurement of three independent flow properties at the same point in a flow field.

ACKNOWLEDGEMENTS

Thanks are due to Mr. Stig Lundgren and Dr. Georg Drougge at the FFA for the many fruitful discussions during the work. Thanks are also due to the technical staff of the FFA for help in performing the experiments, to Mrs. Evy Brostedt for the typing and drawing of figures, and to Åsa Carlson for proof-reading of the manuscript.

SYMBOLS

$f(M)$	$\rho u^2 / p_s$
M	Mach number
p	Pressure
Re	Reynolds number
r_p	Recovery factor of a probe
T	Temperature
u	Velocity
V	Volume
y	Distance from wall
γ	Ratio of specific heats
$[\theta]_{ln}$	Logarithmic mean temperature
ρ	Density

Indices

∞	Infinity
s	Stagnation conditions behind a normal shock
o	Stagnation conditions
m	Measured
v	Refers to conditions in measuring volume
w	Wall

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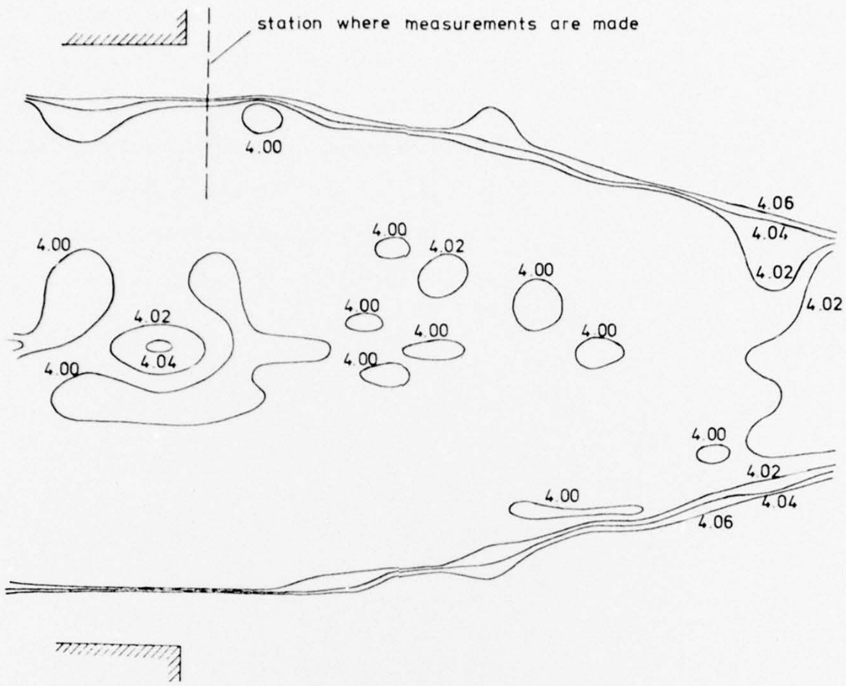

Fig. 1. Lines of constant Mach number. $M_{nom} = 4$.

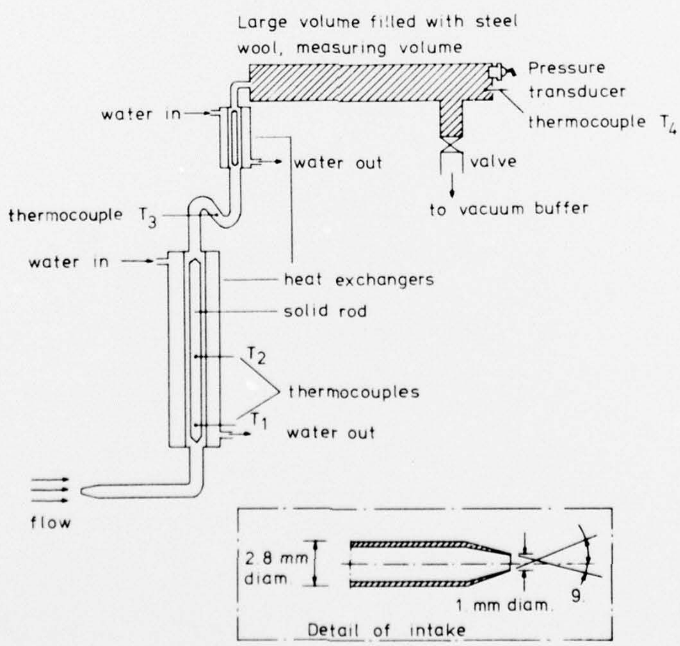

Fig. 2. The FFA mass-flow measuring system. Schematic arrangement.

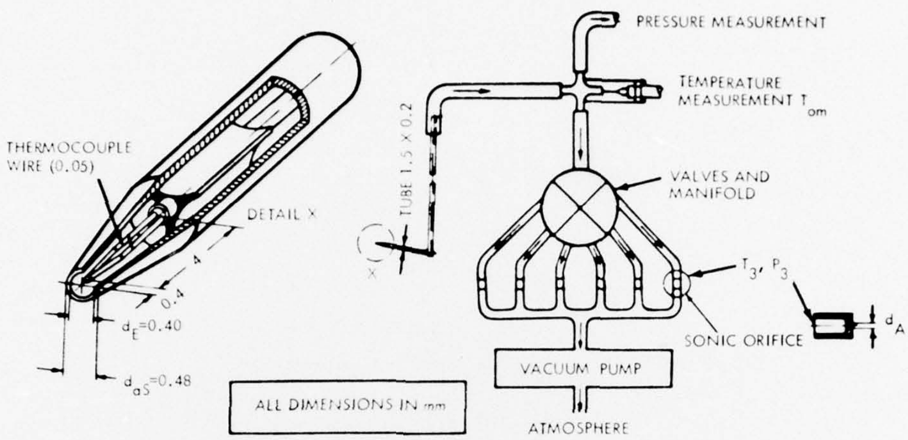

Fig. 3. The AVA combined pressure-temperature probe (from [7]).

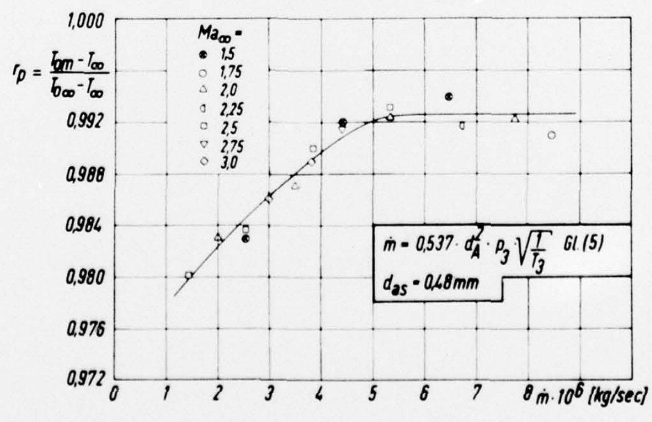

Fig. 4. The recovery factor vs mass flow through the AVA combined pressure-temperature probe (from [7]).

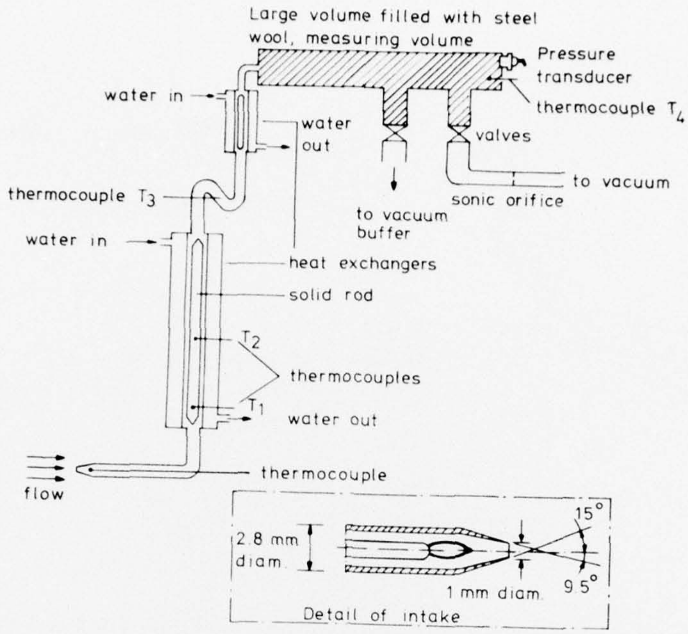

Fig. 5. The combined mass-flow-stagnation-temperature measuring system. Schematic arrangement.

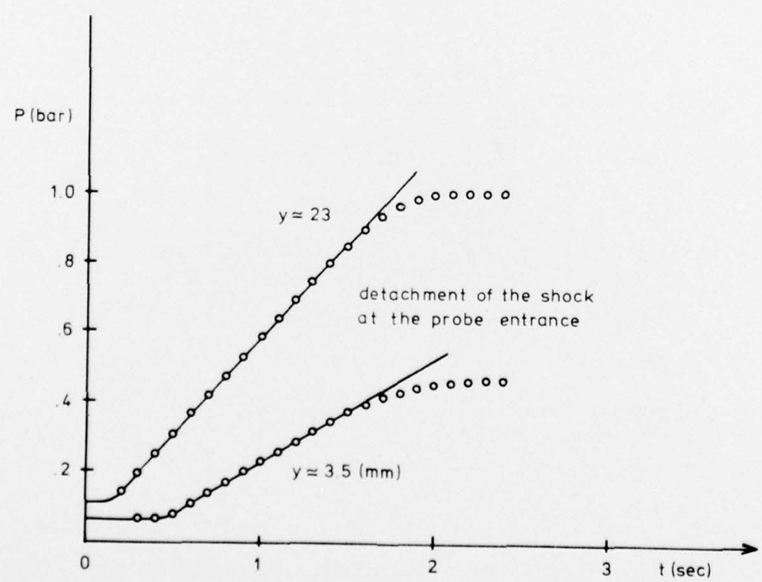

Fig. 6. Typical pressure recordings for mass-flow measurement.

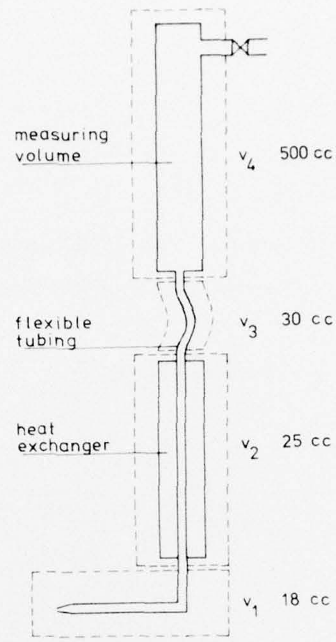

Fig. 7. The various subvolumes of the mass-flow system.

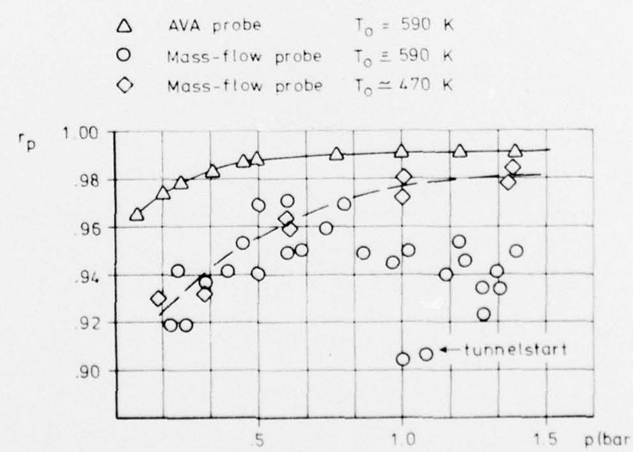

Fig. 8. Recovery factors vs. mass-flow at different stagnation temperatures.

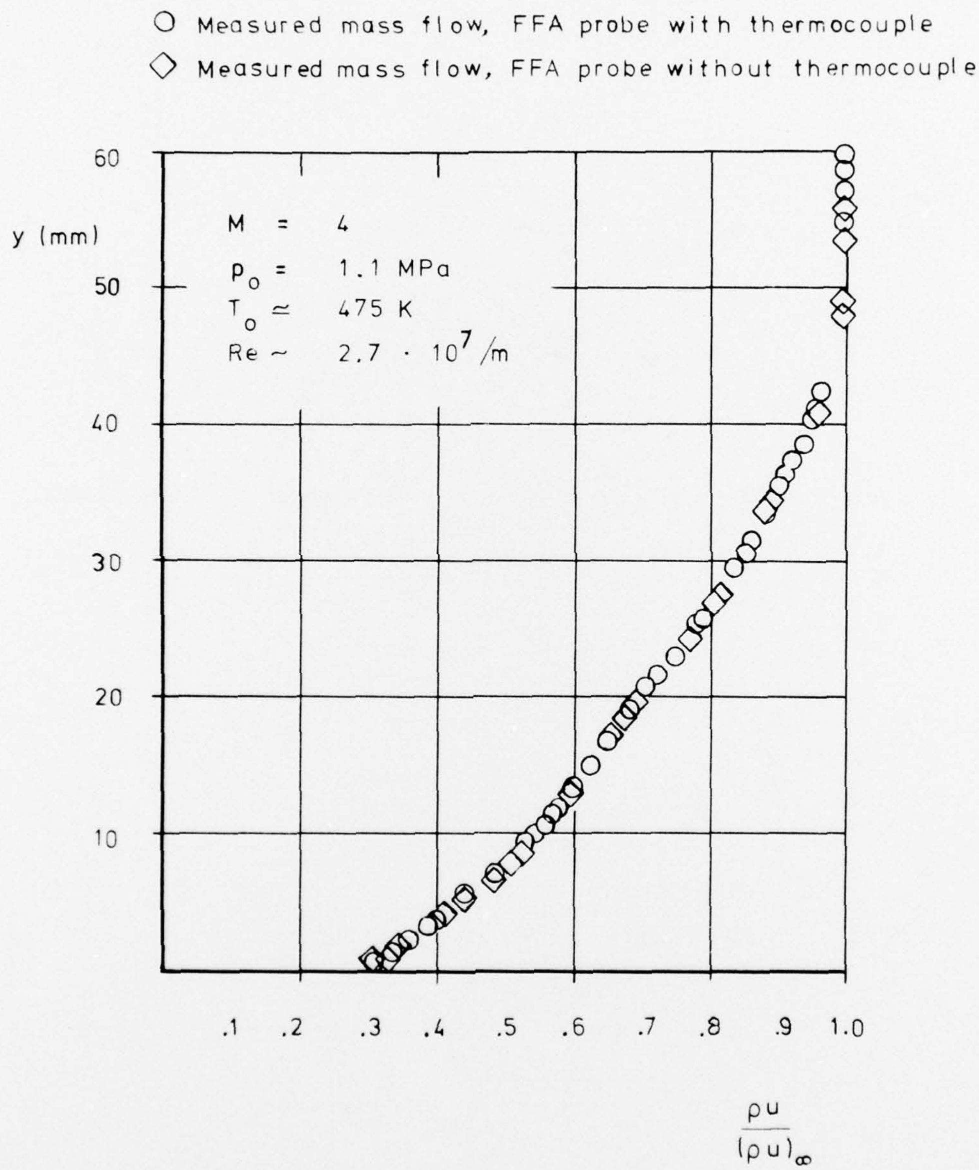

Fig. 9. The normalized mass flow in the boundary layer obtained from measurements with a pure mass-flow probe, and one equipped with a thermocouple.

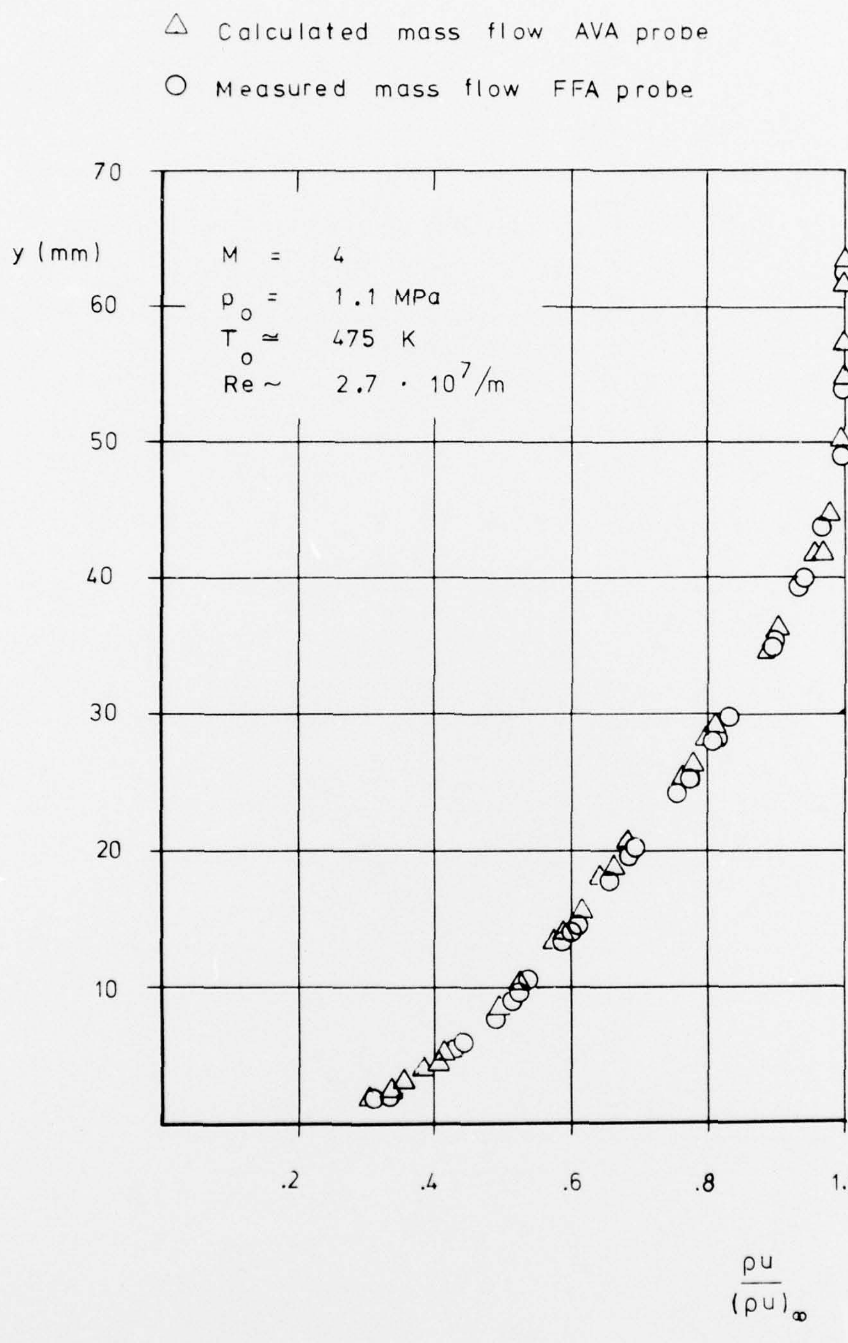

Fig. 10. The normalized mass flow in the boundary layer from measurements with the mass-flow prove and the AVA combined pressure-temperature probe.

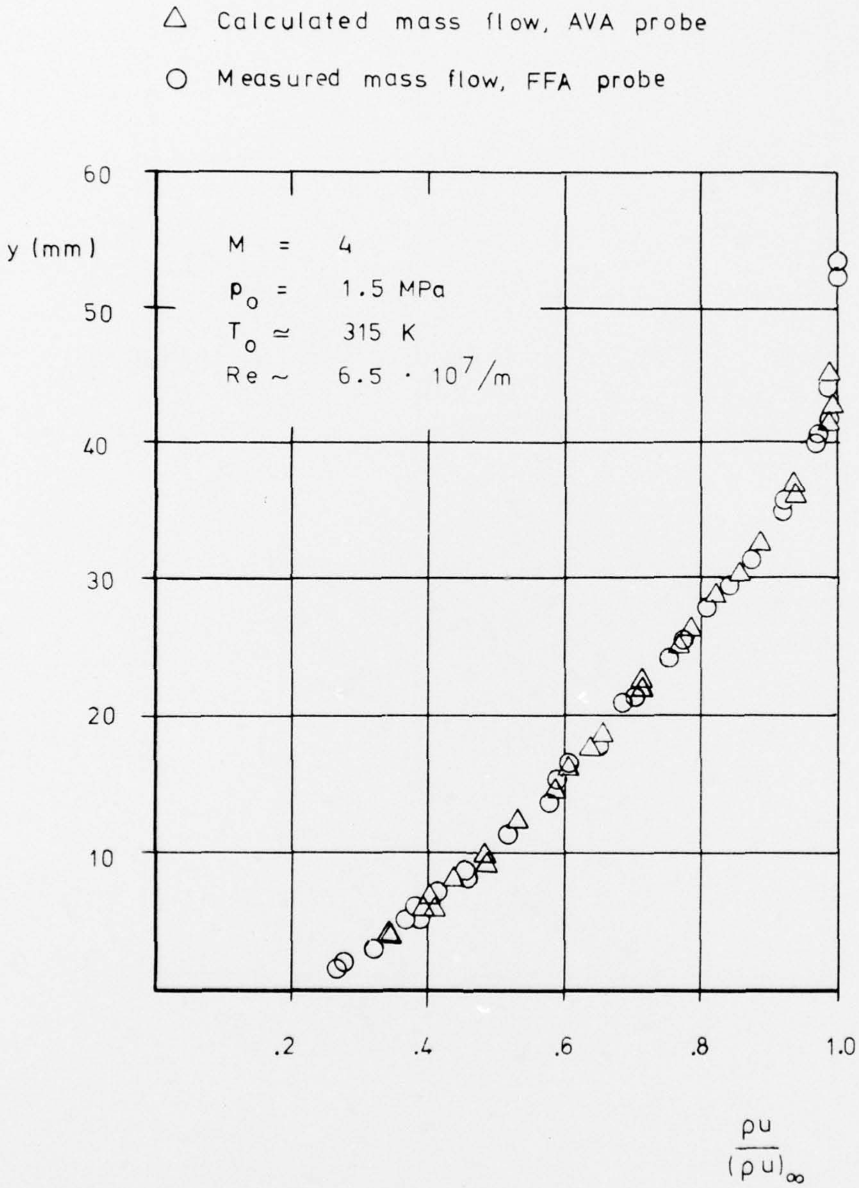

Fig. 11. The normalized mass flow in the boundary layer from measurements with the mass-flow probe and the AVA combined pressure-temperature probe.

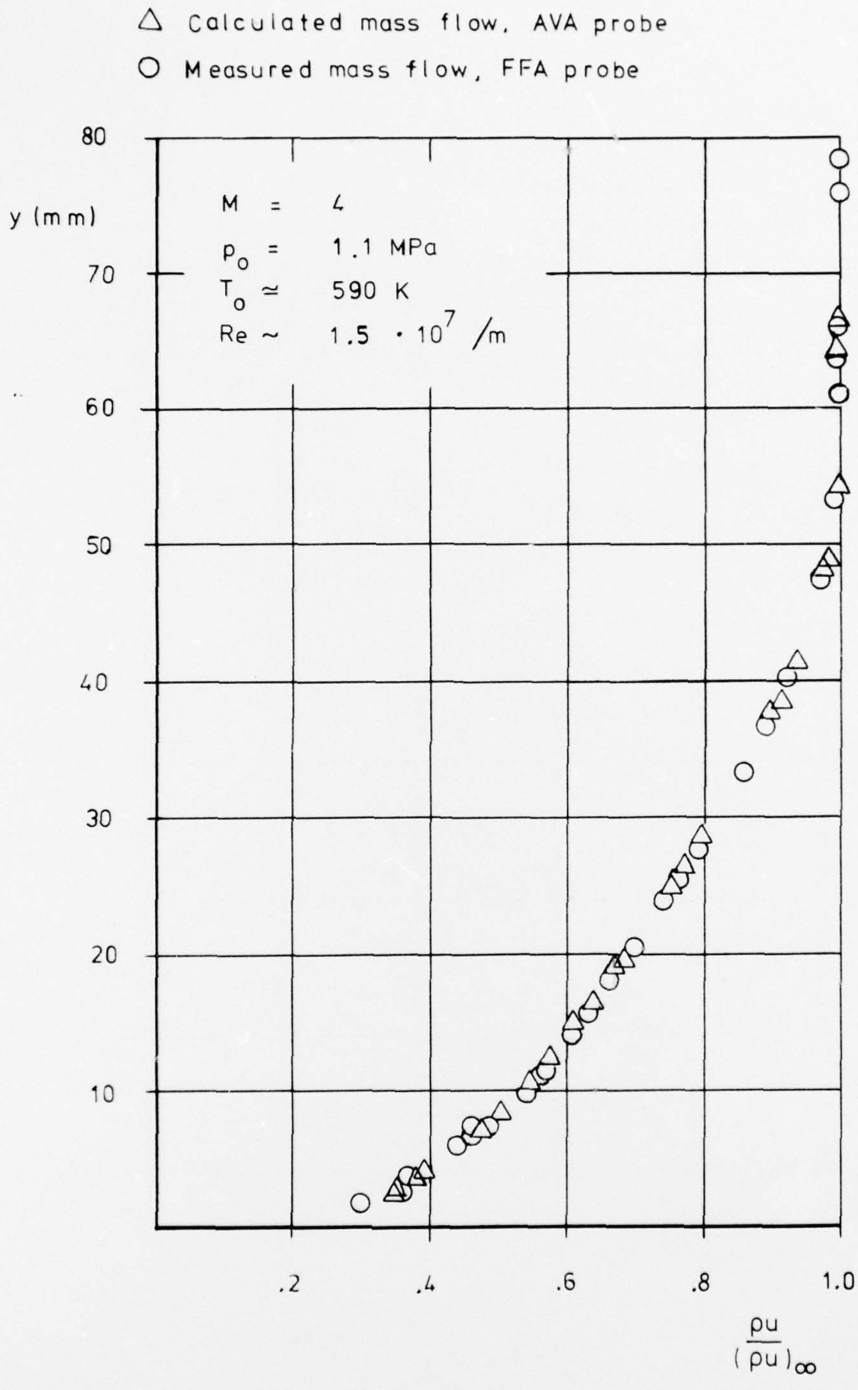

Fig. 12. The normalized mass flow in the boundary layer from measurements with the mass-flow probe and the AVA combined pressure-temperature probe.

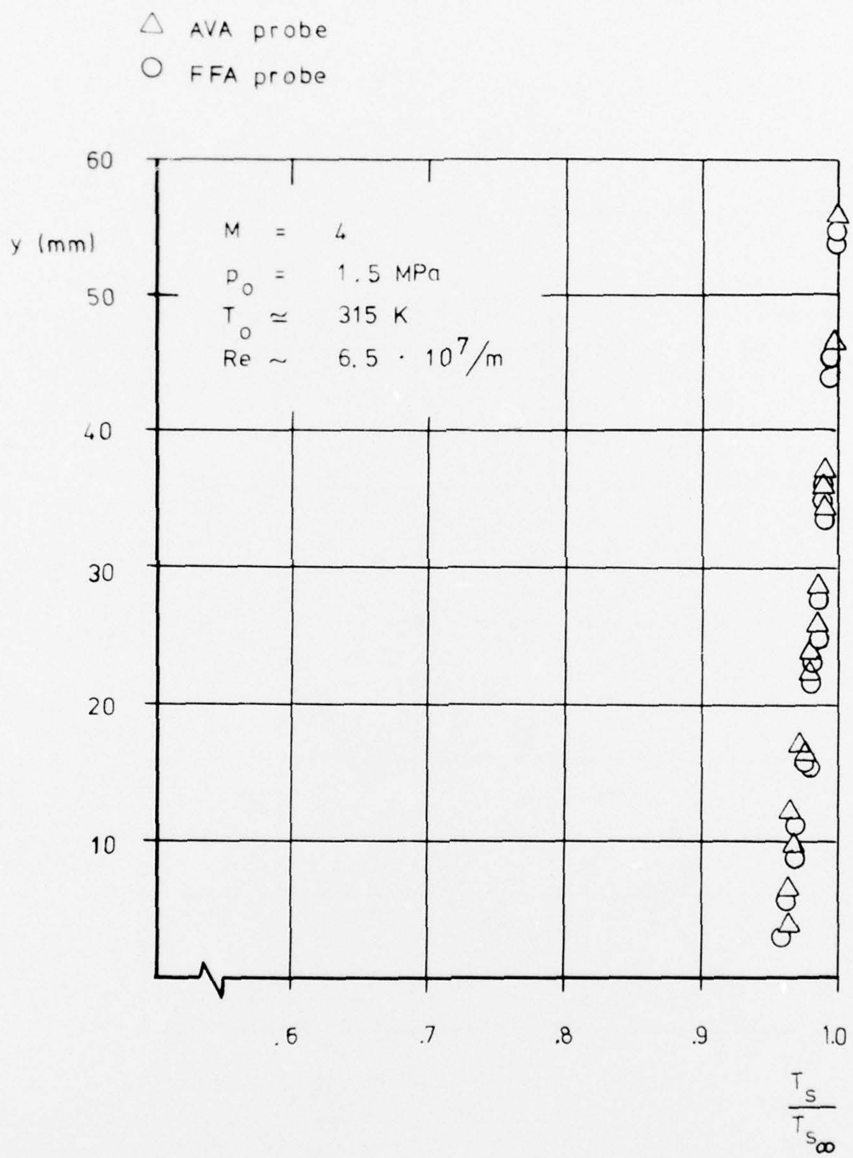

Fig. 13. The normalized temperature distribution in the boundary layer from measurements with the AVA combined pressure-temperature probe and the combined mass-flow-stagnation-temperature probe.

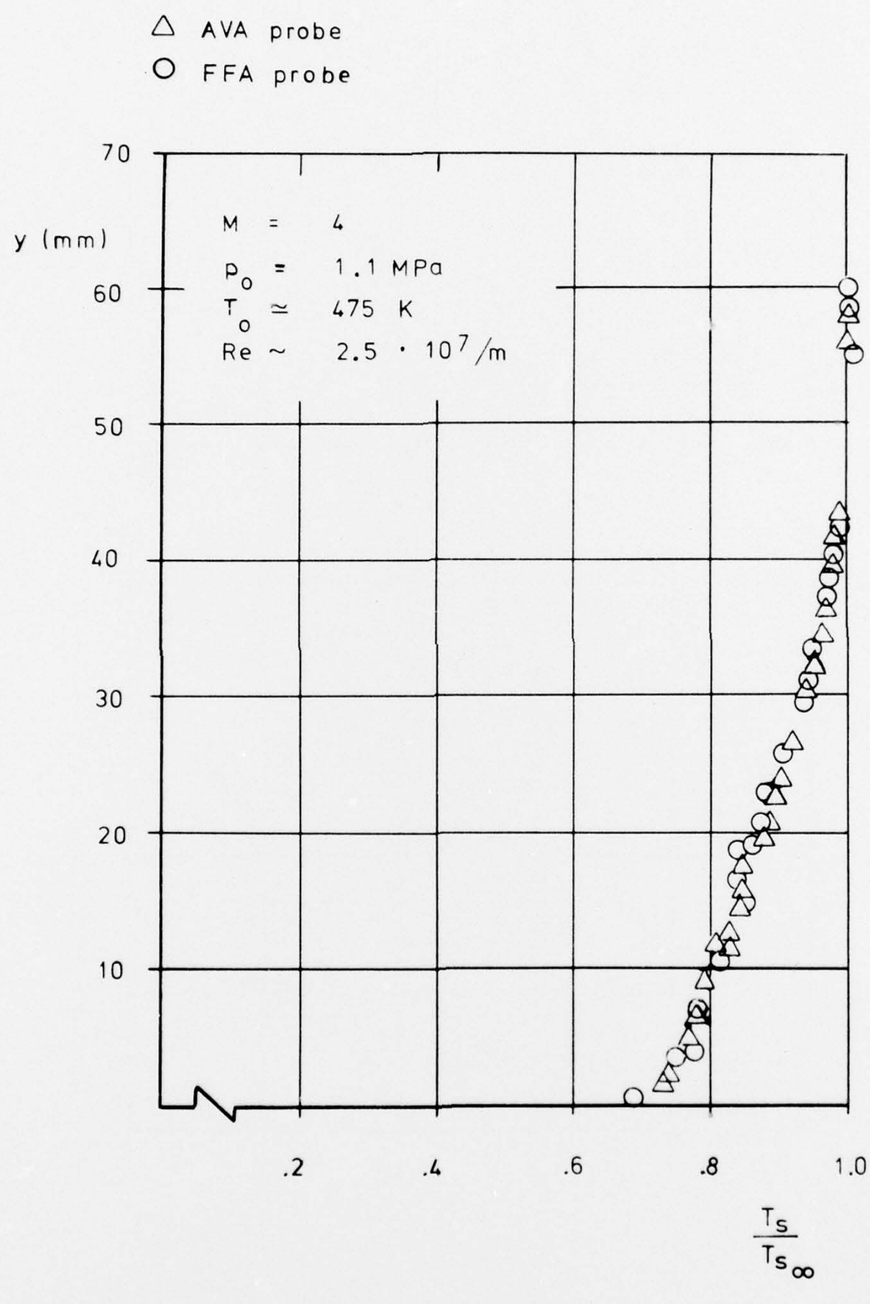

Fig. 14. The normalized temperature distribution in the boundary layer from measurements with the AVA combined pressure-temperature probe and the combined mass-flow-stagnation-temperature probe.

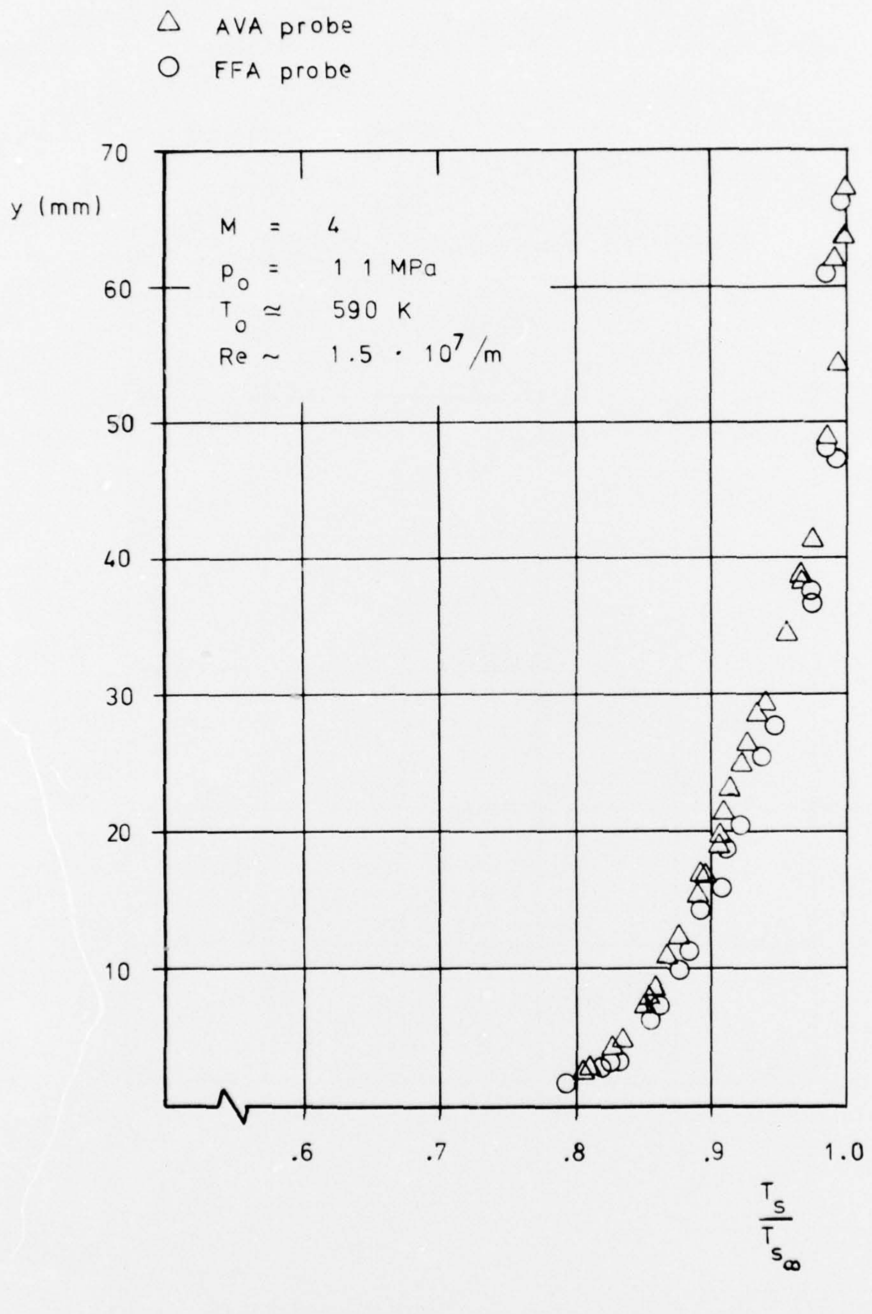

Fig. 15. The normalized temperature distribution in the boundary layer from measurements with the AVA combined pressure-temperature probe and the combined mass-flow-stagnation-temperature probe.

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